Quarkonium measurements in heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV with the STAR experiment

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Quarkonium production mechanism

- Quarkonium production can be factorized into:
  - Perturbative: production of heavy $q\bar{q}$ pair
  - Non-perturbative: quarkonium formation; involves long distances and soft momentum scales
  - Models differ in the treatment of hadronization

Jianwei Qiu, ECT* workshop, 2016
Use quarkonium to probe QGP

• Heavy-quark pairs: early creation & long lived
  • Created mostly before the quark-gluon plasma (QGP) formation
  • Experience entire evolution of QGP

• Dissociation $\rightarrow$ evidence of deconfinement
  • Quark-antiquark potential is color-screened by surrounding partons

• Sequential suppression $\rightarrow$ constrain medium temperature
  • Different quarkonium states of different binding energies dissociate at different temperatures

A. Mocsy, EPJ C61 (2009) 705
The Complications

• Regeneration
  • Much smaller effect for $b\bar{b}$
    $\rightarrow R_{AA}$ measurements

• Cold nuclear matter (CNM) effects:
  • Nuclear PDF: shadowing/anti-shadowing
  • Nuclear absorption
  • Interact with co-movers
  • ...
    $\rightarrow$ Measurements in p+A

• Feed-down
The Solenoid Tracker At RHIC (STAR)

- **Mid-rapidity detector**: $|\eta| < 1$, $0 < \varphi < 2\pi$
  
  ![Diagram of the Solenoid Tracker](image)

  - **TPC**: measure momentum and energy loss
  - **TOF**: measure time of flight
  - **BEMC**: trigger on and identify electrons
  - **MTD** (45% in $\varphi$, $|\eta|<0.5$): trigger on and identify muons
    - Timing measurement ($\sigma \sim 100$ ps) and spatial resolution ($\sim 1$ cm)
    - Facilitate separation of ground and excited $\Upsilon$ states
Quarkonium cross section in p+p collisions

- Inclusive $J/\psi$ and $\Upsilon$ measurements at 200 and 500 GeV:
  - $J/\psi$: models describe the quarkonium production cross-section reasonably well
  - $\Upsilon$: follow world-wide data trend predicted by CEM

2018/10/03
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J/ψ polarization in p+p Collisions

- J/ψ polarization parameters in helicity and Collins-soper frames compared with NRQCD calculations using two sets of Long Distance Matrix Elements (LDMEs)
- NRQCD calculations are consistent with data within uncertainties
- J/ψ polarization at low $p_T$ can be used to constrain the LDMEs

Inclusive $J/\Psi$ $R_{pAu}$ vs. $R_{dAu}$ vs. model

- $R_{pAu}$ is consistent with $R_{dAu}$ within uncertainties
  - $1.4\sigma$ difference at $3 - 6$ GeV/c
- Data favor additional suppression mechanism on top of nPDF effects
\( \psi(2S)/\psi(1S) \) double ratio in pAu

- First double ratio measurement at mid-rapidity at STAR
Upsilon suppression at STAR

• Improved precision of $\Upsilon$ measurements
  • Additional 2016 data are combined with those taken in 2014 and 2011 (di-muon and di-electron results are combined)

• $\Upsilon(2S+3S)$ more suppressed than $\Upsilon(1S)$ in central collisions $\rightarrow$ sequential melting

• Suppression increases from peripheral to central collisions
\( \Upsilon(1S) \) suppression: STAR vs. CMS

- \( \Upsilon(1S) \): compatible with CMS result

\[ \frac{R_{AA}}{N_{\text{part}}} \]

\[ \frac{R_{AA}}{p_T} \text{(GeV/c)} \]

CMS: PLB 770 (2017) 357

\[ \Upsilon(1S) \rightarrow \mu^+\mu^- \text{, } |y|<0.5 \]

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\( \Upsilon(2S+3S) \) suppression: STAR vs. CMS

• \( \Upsilon(2S+3S) \): indication of less suppression at RHIC than at LHC in peripheral collisions

2018/10/03

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\( \Upsilon \) suppression: data vs. models

- Rothkopf:
  - Lattice-vetted heavy-quark potential embedded in a hydrodynamically evolving medium
  - No CNM or regeneration effect

- Rapp:
  - T-dependent binding energy; Kinetic rate equation
  - Includes CNM and regeneration effects

- Both models show agreement with the \( \Upsilon(1S) \) data from STAR
- Rothkopf model seems to underestimate the \( \Upsilon(2S+3S) \) \( R_{AA} \) in the 30-60% centrality
Summary

• p+p
  • Models describe the quarkonium production cross-section reasonably well
  • J/ψ polarization at low $p_T$ can be used to constrain the LDMEs

• p+Au
  • J/ψ $R_{pAu}$ measurement: additional suppression mechanisms seem to be favored by data, but nPDF effects only cannot be fully ruled out yet

• A+A
  Υ(1S):
  • Indication of stronger suppression towards central collisions
  • Similar suppression as that at the LHC
  • Consistent with model predictions

  Υ(2S+3S):
  • More suppressed than Υ(1S) in 0-10% central collisions $\rightarrow$ sequential melting
  • Indication of less suppression at RHIC than at the LHC in peripheral collisions
Thank you!